Energy Conversion and Management 91 (2015) 280–291

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Dynamical and quasi-static multi-physical models of a diesel internal combustion engine using Energetic Macroscopic Representation

L. Horrein [a,b], A. Bouscayrol [a,*], Y. Cheng [b], M. El Fassi [b]

[a] University of Lille1, Laboratory L2EP, Villeneuve d'Ascq/MEGEVH network, France
[b] PSA Peugeot Citroën, Vélizy Villacoublay/MEGEVH network, France

ARTICLE INFO

Article history:
Received 21 April 2014
Accepted 7 December 2014
Available online 24 December 2014

Keywords:
ICE
Static modeling
Dynamical modeling
Energetic Macroscopic Representation
EMR

ABSTRACT

In the simulation of new vehicles, the Internal Combustion Engine (ICE) is generally modeled by a static map. This model yields the mechanical power and the fuel consumption. But some studies require the heat energy from the ICE to be considered (i.e. waste heat recovery, thermal regulation of the cabin). A dynamical multi-physical model of a diesel engine is developed to consider its heat energy. This model is organized using Energetic Macroscopic Representation (EMR) in order to be interconnected to other various models of vehicle subsystems. An experimental validation is provided. Moreover a multi-physical quasi-static model is also derived. According to different modeling aims, a comparison of the dynamical and the quasi-static model is discussed in the case of the simulation of a thermal vehicle. These multi-physical models with different simulation time consumption provide good basis for studying the effects of the thermal energy on the vehicle behaviors, including the possibilities of waste heat recovery.

1. Introduction

The automotive sector has to face the greenhouse gas challenge and petroleum depletion. More efficient and less pollutant vehicles have to be developed [1]. Different solutions are studied nowadays. For example, new combustion modes of thermal vehicles (TVs) aim to reduce the pollutions while increasing the thermal efficiency of the Internal Combustion Engines (ICEs) [2]. In thermal vehicle the waste heat energy is about one third of the total energy. Waste heat recovery systems (WHR) are also developed to increase the overall efficiency of ICE [3], in particular thermoelectric conversion systems [4]. Hybrid electric vehicles (HEVs), electric vehicles (EVs) and fuel cell vehicles (FCVs) are other solutions [5]. However, HEVs are generally considered more suitable for the moment because they balance the cost and the current available technologies [6,7]. New vehicles are thus developed including more efficient subsystems.

Simulation is a key step for the design and the management of such complex vehicles [8,9]. As the vehicle propulsions are composed of more multi-physical sub-systems, the combination of different models is a challenging task [10]. Graphical formalisms are increasingly used to interconnect, in the best way, different kinds of models: Bond-Graph [11], Energetic Macroscopic Representation (EMR) [12], Power-oriented graph [13], etc. Bond-graph is more dedicated for vehicle propulsion design [14]. EMR is a graphical description, which aims to organize different kinds of model in a unified way. Only four elements are considered: energy sources, energy storage, energy conversion (without energy storage) and energy distribution (see Appendix). All elements are connected according to the action reaction principle to highlight the exchanged power. Because only the physical causality (i.e. integral causality [15,16]) is considered, EMR enables a systematic deduction of the control structures of complex systems [17–20]. For that, EMR is more dedicated for vehicle control and energy management. It should be noticed that actual vehicle software for vehicle, such as Dymola [21] or Cruise [22], are developed on a structural approach [10], where different component from library can be easily connected to simulate a vehicle. However the development of their control should be developed in a heuristic way from the expertise of the users. Using a functional approach, their control can be developed in a more systematic way, while the interconnection of subsystems should take care of conflict of association [10].

For the global assessment of new thermal or hybrid vehicles, the ICE is a key element. Generally static efficiency maps are considered for a global study [6,10,23]. For example, in the EMR formalism the ICEs are thus considered as source element described by look-up tables [17,18,20]. But in these static maps, only the mechanical power is given as well as the calculated fuel consumption. No thermal effects are given and the impacts of the ICE on the cabin temperature or the waste heat recovery (WHR) technologies

* Corresponding author. Tel.: +33 (0)3 20 43 42 53; fax: +33 (0)3 20 43 69 67.
E-mail address: Alain.Bouscayrol@univ-lille1.fr (A. Bouscayrol).

http://dx.doi.org/10.1016/j.enconman.2014.12.022
0196-8904/

can thus not be studied. More dynamical and complex models of ICE are used for the ICE design and control [2,24]. But they are generally too complex and time consuming to be to be involved in the global simulation of a vehicle. Some intermediate models have been used through EMR [25] but without a detailed description of the thermal energies. A pure thermal model (thermal inertia) of an ICE has been also introduced using EMR of the description of the cooling system of a thermal vehicle [26].

In this paper, a dynamic and a quasi-static multi-physical models of a diesel engine are developed using EMR. This ICE description will enable to predict the energy distribution of the ICE, including the thermal energy. As many thermal, hybrid and electric vehicles have already been descried using EMR (to deduce a systematic control structure), the developed ICE description can be easily connected to the power train of these vehicles This will enable to integrate these ICE models into a global vehicle simulation in order to evaluate different technologies, especially the thermal applications. This description will present more physical information as well as reasonable computation time.

In Section 2, a dynamical multi-physical model of an ICE is organized according to EMR. An experimental validation is also proposed. In Section 3 a quasi-static model is derived from the dynamical model. Four look-up tables are defined for the mechanical and thermal powers, and a comparison with the experimental tests has been done. In Section 4, both models are integrated in a global simulation of a thermal vehicle thanks to EMR. Finally, the advantages of both models are discussed.

2. Dynamical multi-physical ICE description

2.1. Dynamical multi-physical model

In the Internal Combustion Engine (ICE), the mechanical conversion, the thermal transfer with the cooling system and the thermal power evacuated with the exhaust gas depend on the instantaneous values of the internal temperature and the internal pressure (see. the following equations). Because these two parameters are state variables, a dynamical model is needed to know with accuracy the instantaneous pressure and temperature in each cylinder and to deduce the power distribution in the engine [2,27].

A nomenclature of the variables, parameters and subscripts is presented in appendix A.

The IC engine converts the chemical power due to the ignition P_i into mechanical P_m and thermal power. The thermal power is evacuated in the exhaust gas P_e and transferred into the cooling system P_c (Fig. 1). The instantaneous difference between the input and output powers are stored in the gas (U_g internal energy storage):

$$P_m = P_i - P_c - P_e - \frac{d}{dt}U_g \tag{1}$$

The temperature T_g change in function of this storage energy [24]:

$$\frac{d}{dt}U_g = m_g C_{p\_g}\frac{d}{dt}T_g \tag{2}$$

with m_g the mass of the gas inside the cylinder. The gas calorific capacity (C_{p_g}) depends on the chemical gas composition [28]. The gas calorific capacity (C_{p_g}) depends on calorific capacities of each

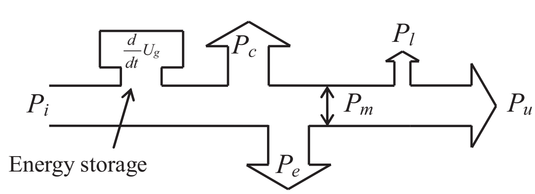

Fig. 1. Power balance in the IC engine.

chemical species C_{p_x} making up the gas. The individual gas calorific capacities depend on the temperature and are expressed using relation (3). The coefficients a_{x_i} are deduced from empiric data tables [28].

$$C_{p\_x} = \sum_{i=-2}^{4} a_{x\_i} T^i \tag{3}$$

The energy balance is realized on each cylinder. The following relations are given for one cylinder. The cylinder behavior will be generalized later to consider the complete engine.

2.1.1. Chemical power

The combustion between the fuel and the air produces a thermal power. This power is estimated in function of the mass flow rates of the air q_{m_a} and the fuel q_{m_f} and also of the internal properties of the fuel. The LHV (low heating value) expresses the internal potential energy of the fuel:

$$P_i = q_{m\_f}LHV + q_{m\_a}C_{p\_a}T_a \tag{4}$$

with T_a the temperature during admission stroke. The air calorific capacity C_{p_a} is expressed using (3).

2.1.2. Gas internal energy storage

Relations (1) and (2) show the link between the temperature and the power. These relations translate an energy accumulation in the gas. This thermal energy storage in the gas U_g can be written:

$$U_g = m_g C_{p\_g} T_g \tag{5}$$

2.1.3. Mechanical power

From the gas temperature inside the cylinder, the pressure in the cylinder p_r can be estimated with the ideal gas law:

$$p_r V_{cyl} = n_g R T_g \tag{6}$$

With n_g the gas mole number and R the perfect gas constant. The instantaneous volume of the cylinder V_{cyl} is defined in function of the rotation speed Ω_m and the mechanical parameters of the connecting rod and the crank mechanism k_0, k_1, k_2, k_3: (Fig. 2) [29]

$$\theta = \Omega_m t \tag{7}$$

$$V_{cyl} = k_0 - k_1\left(k_2\cos(\theta) + k_3\sqrt{1 - \left(\frac{k_2}{k_3}\right)^2 \sin(\theta)^2}\right) \tag{8}$$

To produce the mechanical power P_m, one part of the thermal power is transformed into hydraulic power and then into the mechanical power.

$$P_m = q_{v\_cyl}p_r \tag{9}$$

$$P_u = P_m - P_l = \Gamma_m\Omega_m - \Gamma_l\Omega_m \tag{10}$$

To make a difference with the temperature, the torque is noted Γ. The losses due to the thermal–hydraulic conversion and hydraulic-mechanical conversion are grouped in an equivalent friction torque Γ_l.

As the instantaneous volume, the volume flow rate is determined in function of the rotation speed Ω_m and mechanical parameter k_2, k_3, k_4 from the derivation of relation (8) [29]:

$$q_{v\_cyl} = k_4\left(1 + \frac{\cos(\Omega_m t)}{k_3\sqrt{1 - ((k_2/k_3)\sin(\Omega_m t))^2}}\right)\Omega_m \sin(\Omega_m t) \tag{11}$$

2.1.4. Thermal power transferred in the cooling system

To describe the heat exchange between the cylinder and the engine block, a convection model is used: